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Carbon embodied optimization for buttressed earth-retaining walls: Implications for low-carbon conceptual designs

Francisca Molina-Moreno [a], José V. Martí [b], Víctor Yepes [b, *]

[a] Dept. of Transport Infrastructure and Engineering, Universitat Politècnica de València, 46022 Valencia, Spain
[b] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022 Valencia, Spain

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ABSTRACT

This paper shows the differences between the design of a reinforced concrete structure considering two objectives to minimize; economic cost and CO_2 emissions. Both objectives depend on the amount of two high carbon intensive materials: cement in the concrete and steel; therefore, these objectives are related. As the balance between steel and cement per m^3 of concrete depends on several factors such as the type of structure, this study focuses on buttressed earth-retaining walls. Another factor that determines the balance between steel and concrete is the height of the wall. Thus, the methodology considers a parametric study for optimal designs of buttressed earth-retaining walls, where one of the parameters is the wall height. One of the objectives is to show the variation in cost when CO_2 is minimized, respectful of minimizing the economic cost. The findings show that wall elements under bending-compressive strains (i.e. the stem of the buttressed retaining wall) perform differently depending on the target function. On one hand, the study reveals an upward trend of steel per unit volume of concrete in emission-optimized earth-retaining buttressed walls, compared to the cost-optimized. On the other hand, it is checked that unlike the cost-optimized walls, emission-optimized walls opt for a higher concrete class than the minimum class available. These findings indicate that emission-optimized walls penalize not only concrete volume, but also the cement content, to the extent that a higher concrete class outperforms in reduced emissions. Additionally, the paper outlines how and to what extent the design of this typology varies for the two analyzed objectives in terms of geometry and amount of materials. Some relevant differences influencing the geometry of design strategies are found.

1. Introduction

Carbon emissions represent one of the largest contributions to global warming so the reduction of carbon-intensive products in structural engineering is of wider concern. Emissions are to be determined for every structure, so CO_2 is currently investigated as an optimization target. Yepes et al. (2012), analyzed the implications of both optimization objectives in cantilever earth-retaining walls. Subsequent studies considered multiobjective optimization of cost and carbon-emissions. Yepes et al. (2015), considered cost and emissions in the comparative optimization of cast–prestressed concrete U-beam road bridges, concluding that the two objectives lead to slightly different solutions. Subsequent studies (García-Segura and Yepes, 2016; Martí et al., 2016) considered the optimization towards the two objective functions in post-tensioned concrete box-girder road bridges.

Unlike the aforementioned studies, this research considers only passive instead of prestressed reinforcement. The efficiency of pursuing a low-carbon strategy against a reduced cost one is tested through this study. One of the objectives is to differentiate between CO_2 emissions and cost functions according to the mechanical behavior of structures. Traditionally, the economical factor has conventionally been the mainstream objective to minimize, so the ratio of reinforcement (kg/m^3) is a classic feature used to benchmark minimum cost and carbon alternatives. One of the objectives of the present study is to quantify how much the optimization target influences on the different reinforcement rates of the wall. However, the ratio of reinforcement does not seem to be the unique indicator of environmental efficiency, given that the environmental performance of concrete is also sensitive to the best cement manufacturing technology available (Kajaste and Hurme, 2016) and

* Corresponding author.
E-mail addresses: framomo4@upvnet.upv.es (F. Molina-Moreno), jvmartia@cst.upv.es (J.V. Martí), vyepesp@cst.upv.es (V. Yepes).

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the recycled steel rate, as shown in previous work for the type of structure analyzed in this paper (Zastrow et al., 2017).

Another point of interest lies in the fact that embodied emissions of concrete are conditioned to the content of clinker in the concrete dosages. Conversely, mixes are not uniform along the concrete classes, and so do the necessary volumes in reinforced structural wall elements. Furthermore, as the mechanical behavior of reinforced concrete bending-compressive structural elements is dependent on both concrete and steel reinforcement together, little relationship is possible among design variables and the concrete class f_{ck}, exclusively. These reasons, together with the non-linear structural behavior do not allow for a possible straightforward relationship between emissions and the use of a specified compressive strength in a concrete structure. It is studied whether there is some range for minimizing emissions by using higher concrete classes. A research need was identified when it comes to evaluate the convenience of using a greater compressive strength, whenever it procures fewer emissions. In this sense, the studies of Habert and Roussel (2009), proved that greater strength allows for a reduction in concrete volume in structures that carry only their own weight. Habert et al. (2012), studied whether an improvement in concrete strength would produce a significant difference on the bridge of study. It pointed out the life cycle impact results of a traditional and high performance concrete in two bridge solutions. García-Segura et al. (2014), compared four different compressive strength classes in their studies of precast prestressed bridges. Next, García-Segura et al. (2015), also analyzed the influence of the objective function in the amount of concrete and steel in the beams and slab of the bridge. Their conclusions about the influence of the emission objective on the volume of concrete led us to undertake the comparison of objective functions in other structural typologies.

The methodology for the optimization is the use of a heuristic procedure, Harmony Search (HS). HS was also built upon life cycle cost and embodied emissions of buildings (Fesanghary et al., 2012) and columns (Kripka and de Medeiros, 2012) in the definition of conceptual design guidelines. In alignment with our work, the CO_2 optimization in reinforced concrete structures, like building frames, was previously analyzed by Paya-Zaforteza et al. (2009) with Simulated Annealing algorithm and later Camp and Assadollahi (2013) performed a multiobjective optimization considering not only CO_2 but also economic costs. The comparison of CO_2 and cost optimizations has not been performed yet in with the purpose of obtaining design implications of either target functions. Therefore, our work undertakes this task.

Previous studies analyzed the influence of the type of fill and maximum bearing capacity on the variables of cost optimized solutions of earth retaining cantilever (Yepes et al., 2008) and buttressed walls (Molina-Moreno et al., 2017). The carbon embodied target is narrowly linked to economical designs in cantilever walls (Yepes et al., 2012) and is presumed a potentially suitable target in other types of wall.

The constraint-based design definition is described in Section 2 and the optimization algorithm is described in Section 3. The analyses of cost and emission-optimized results are shown in Section 4, for each design variable. Since variations in steel content and concrete might hinder economic and environmental differences, Section 4 includes a comparative analysis of results of a carbon-embodied optimization by fixing f_{ck} as one of the influential parameters on global warming potential. Finally, Section 5 summarizes the main outcomes.

2. Design problem definition

Two objective functions $f(\boldsymbol{x})$ are considered: embodied emissions and construction cost of the wall. The functions consider the unit CO_2 equivalent emissions e_i and prices p_i and the measurements of the corresponding units for each part of the wall. These construction units correspond to materials, formwork and works of excavation and earth-fill. The emission and cost functions are based on a 1 m wide strip. Unit prices and emissions are given in Table 1 and correspond to the values considered in a previous study on earth-retaining walls (Yepes et al., 2008). The ultimate (ULS) and service (SLS) state limits determine the constraints to satisfy, according to Eq. (1).

$$\begin{aligned}&\text{Minimize } f(\boldsymbol{x})\\&\text{Subject to } x_i \in \boldsymbol{X}_i, \qquad i = 1, 2, \ldots, N\end{aligned} \tag{1}$$

where $f(\boldsymbol{x})$ is an objective function where x is the set of each decision variable x_i; X_i is the set of range of possible values for each variable and N the number of variables. No penalty functions are used, as the problem is restricted to feasible solutions. Therefore, the foremost computational effort lies in the evaluation of the ULS and SLS. Both constraints become possibly critical in selecting the dimensions of the foundations, since the design process does not follow the traditional approach of structural predimensioning and dimensioning.

2.1. Design variables and parameters

The design variables and parameters define the constructive solution. The geometric variables of the buttressed earth-retaining wall under study are depicted in Figs. 1 and 2. The retaining wall is defined by 20 design variables summarized in Table 2. Design parameters are described in Table 3. A standard type of fill (F_2) is considered, corresponding to granular soils with more than 12% of fines (GW, GS, SM, SL) and fine soils with more than 25% of coarse grained soil (size of 45 mm or less) Yepes et al. (2012). Soil is determined by its density γ (20 kN/m^3) and 30° internal friction angle. The maximum bearing capacity considered is 0.3 MPa. Generally, the relative amount of steel and concrete increases the higher the wall is, the less cohesive the ground is and the lower bearing capacity it presents. The set of combinations of the values of the variables constitutes a space of solutions. These variables correspond to geometry, concrete grades and passive reinforcement of the wall. The variables of dimensions and quantities are discrete, to adapt to real cases. The geometric variables are the thickness of the stem (*em*), the thickness of the buttresses (*ec*), the thickness of the footing (*cz*), the length of the toe (*lp*), the length of the heel (*lt*), and the distance between buttresses (*dc*). The steel

Table 1
Unit breakdown of emissions and cost.

Unit	Emissions (CO_2-eq)	Cost (€)
kg of steel B400	3.02	0.56
kg of steel B500	2.82	0.58
m^3 of concrete HA-25 in stem	224.34	56.66
m^3 of concrete HA-30 in stem	224.94	60.80
m^3 of concrete HA-35 in stem	265.28	65.32
m^3 of concrete HA-40 in stem	265.28	70.41
m^3 of concrete HA-45 in stem	265.91	75.22
m^3 of concrete HA-50 in stem	265.95	80.03
m^2 stem formwork	1.92	21.61
m^3 of backfill	28.79	5.56
m^3 of concrete HA-25 in foundation	224.34	50.65
m^3 of concrete HA-30 in foundation	224.94	54.79
m^3 of concrete HA-35 in foundation	265.28	59.31
m^3 of concrete HA-40 in foundation	265.28	64.40
m^3 of concrete HA-45 in foundation	265.91	69.21
m^3 of concrete HA-50 in foundation	265.95	74.02